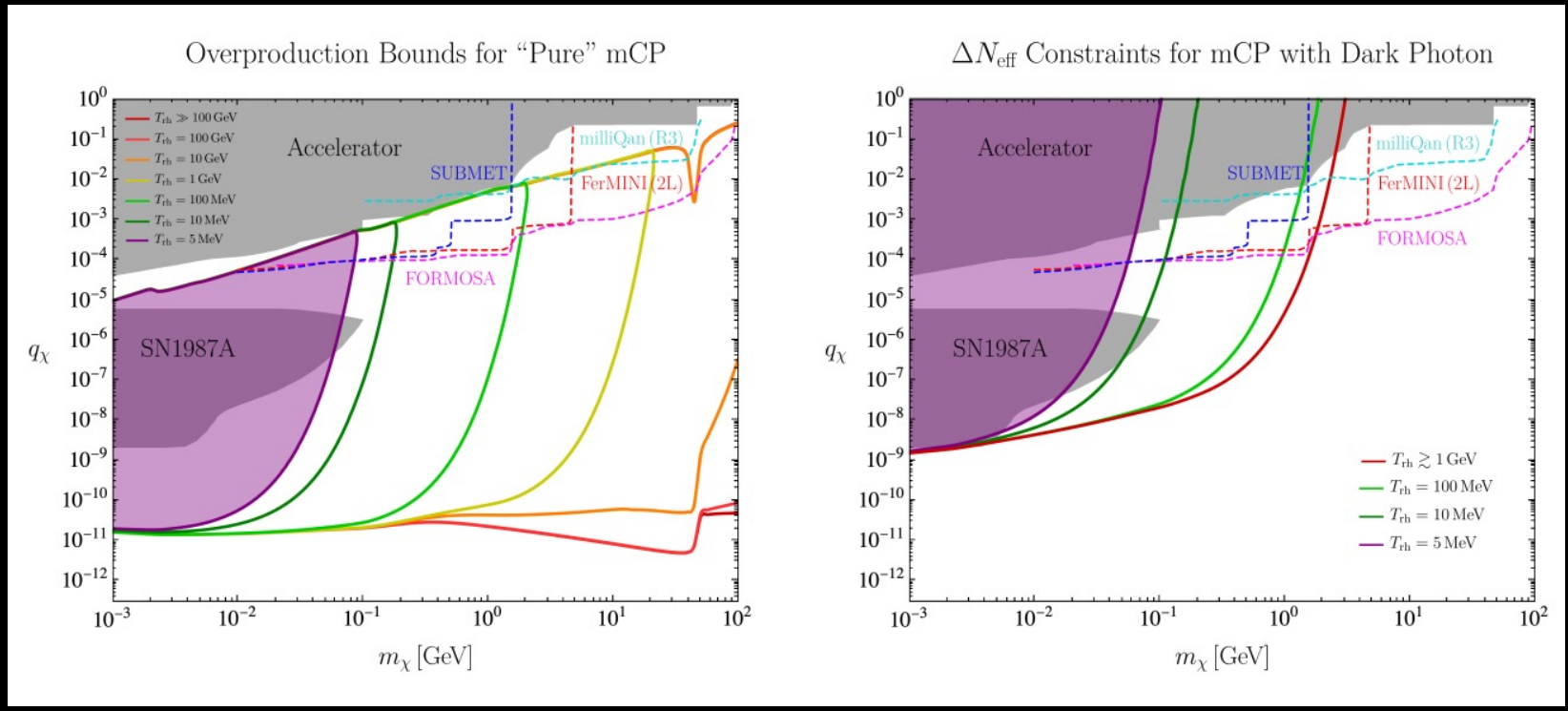
Cosmic Millicharge Background: Probing Fundamental Theory & Reheating Cosmology



Gan, **Tsai**, 2308.07951

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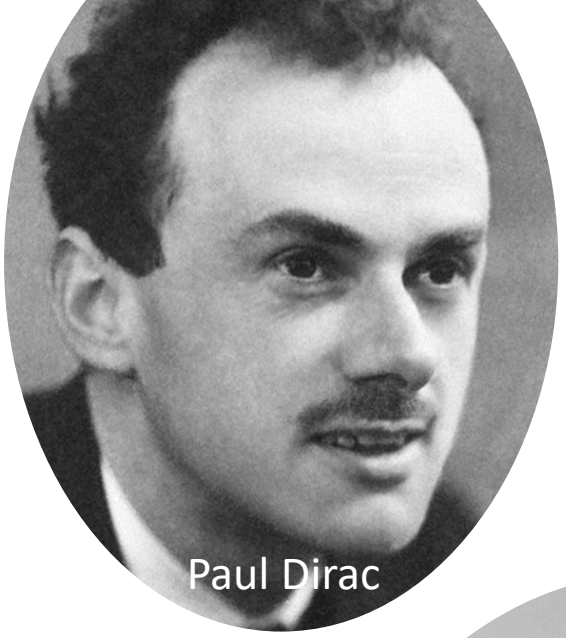
LANL mCP Search: LANSCE-mQ, 2407.07142

Outline


Paul Dirac

- Intro & Motivations
- Probing Reheating Cosmology
- Differentiating two types of mCPs


Frederick Reines

Theoretical Motivations

Millicharged particle (mCP) is a particle χ with {mass, electric charge} = $\{m_\chi, \epsilon e\}$

$\epsilon = Q_x/e$

1. **Is electric charge quantized? To what unit? And why?**
   Long-standing questions:

- Inspired Dirac quantization, Grand Unified Theories (GUTs)

- String theory predicts un-confined fractionally charged particles
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  Conversation: Salam, Sciama, Witten and Budinich (ICTP, 1986)

- More links to string compactification & quantum gravity (Shiu, Soler, Ye, PRL '13)
  + new theoretical developments

2. **Millicharged dark matter Implications & explain CMB absorption spectrum**

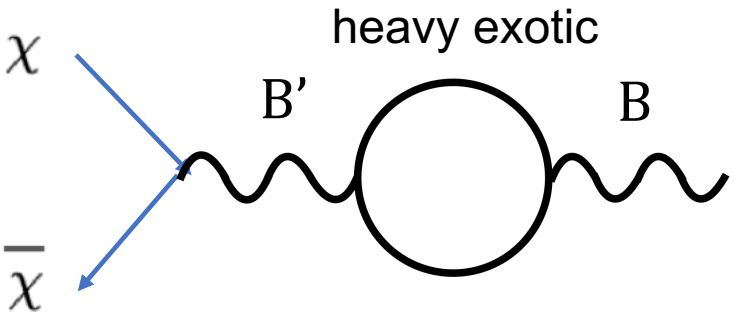
Two Kinds of mCP

"Pure" mCP

- Theoretical implication of mCP with a small (irrational) charge without a dark photon
- Implications on GUTs models
- Implications on string compactifications
  Shiu, Soler, Ye, *PRL* (2013)

Kinetic-mixing mCP

- Compatible with GUTS.

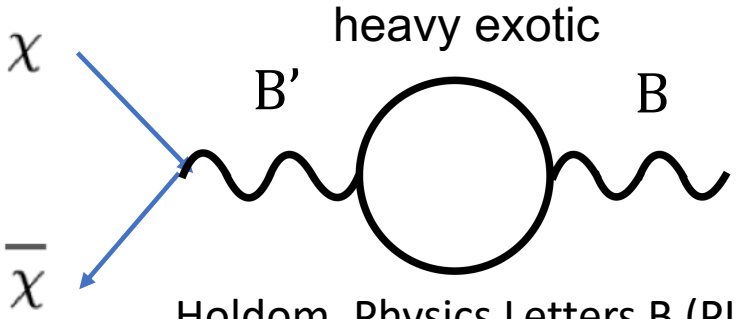


Choose a proper basis: massless dark photon A' decouple from SM

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

Kinetic Mixing mCP

Coupled to new dark fermion χ



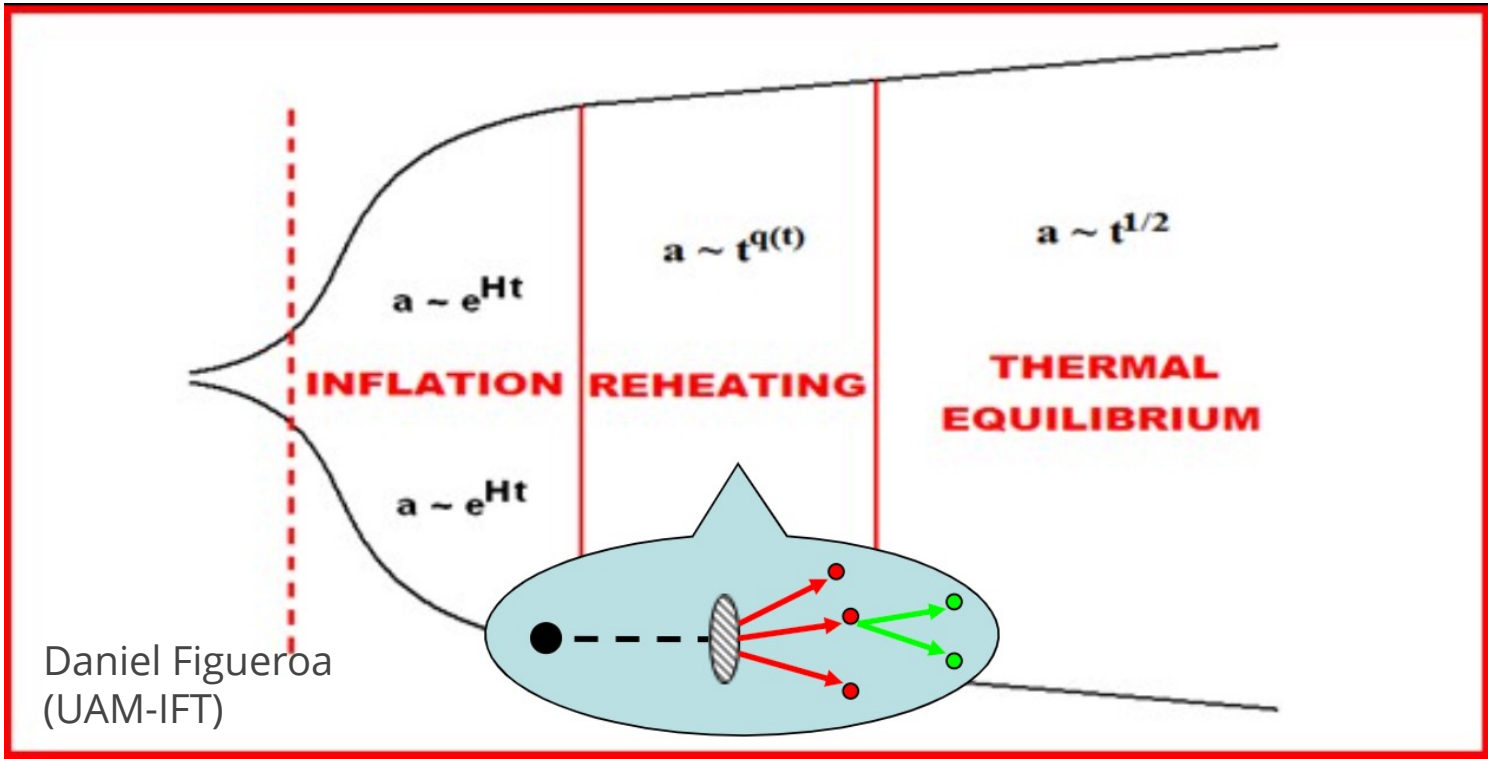
(Standard Model $U(1)_Y$)

Holdom, Physics Letters B (PLB), 1985

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie' \not{B}' + iM_{\rm MCP})\chi$$

- New Fermion χ charged under U(1)'
- Field redefinition into a more convenient basis for massless B', $B' \to B' + \kappa B$
- new fermion acquires a small EM charge Q (the charge of mCP χ): $Q = \kappa e' \cos\theta_W, \quad \epsilon \equiv \kappa e' \cos\theta_W / e.$

Inflation and Reheating



a: scale factor, basically quantifying the size of the Universe
t: time

We know very little about reheating. We don't even know what temperature does it reheat to!

Cosmic Millicharge Background (CmB)
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"Pure" mCP

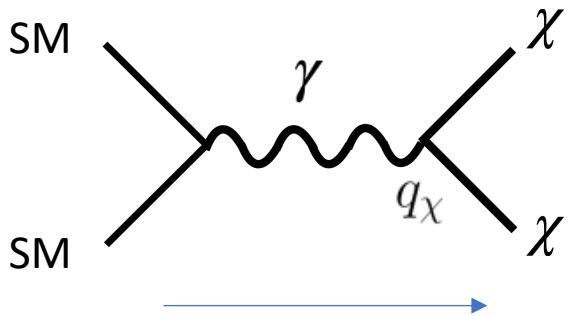
- mCP with a **small (irrational) charge & no dark photon**
- **Indirect test of GUTs models**
- **Indirect test of string compactifications**
  Gan, Shiu, **Tsai**, in progress

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

Irreducible Production during Reheating

Inflaton

Reheating at temperature T_{rh}



"Freeze-in"

"Freeze-out" when it stops

Cosmic Millicharge: Overproduction During Reheating

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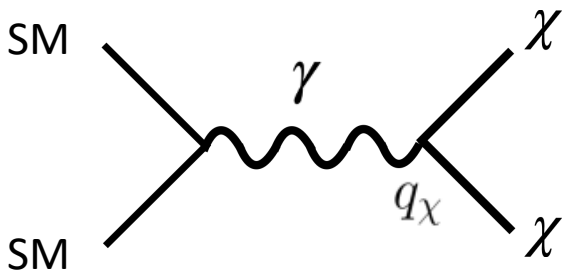
Irreducible Production during Reheating

Inflaton

Reheating at temperature T_{rh}



"Freeze-in"

"Freeze-out" when it stops

mCP can be easily "overproduced", to more than that of the observed amount of dark matter (DM)

$$\Omega_{\rm DM} h^2 \sim 0.12$$

Currently measured DM abundance

$$\Omega \equiv \frac{\rho}{\rho_c}$$

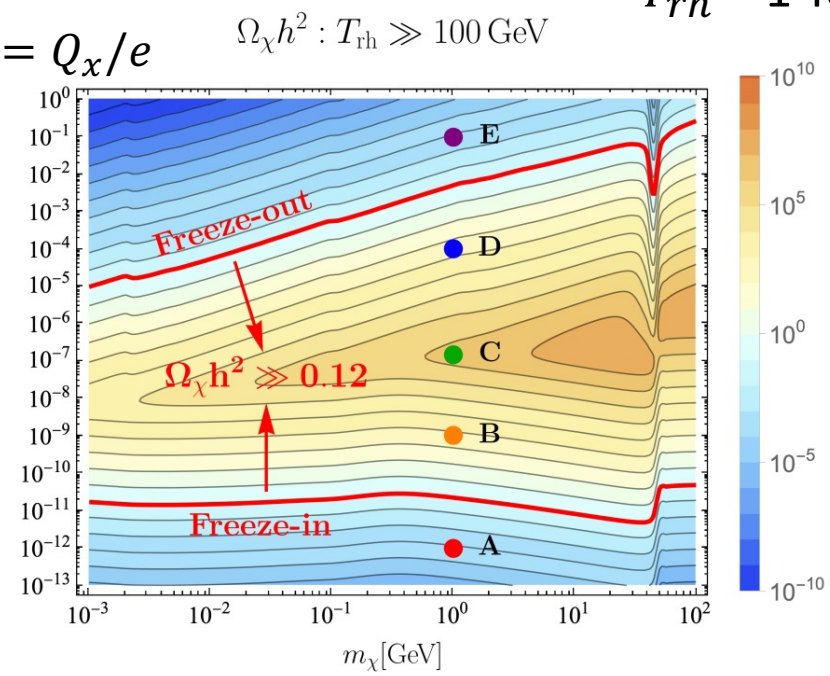
Density is normalized by ρ_c, the critical density for a flat Universe; h = 0.674

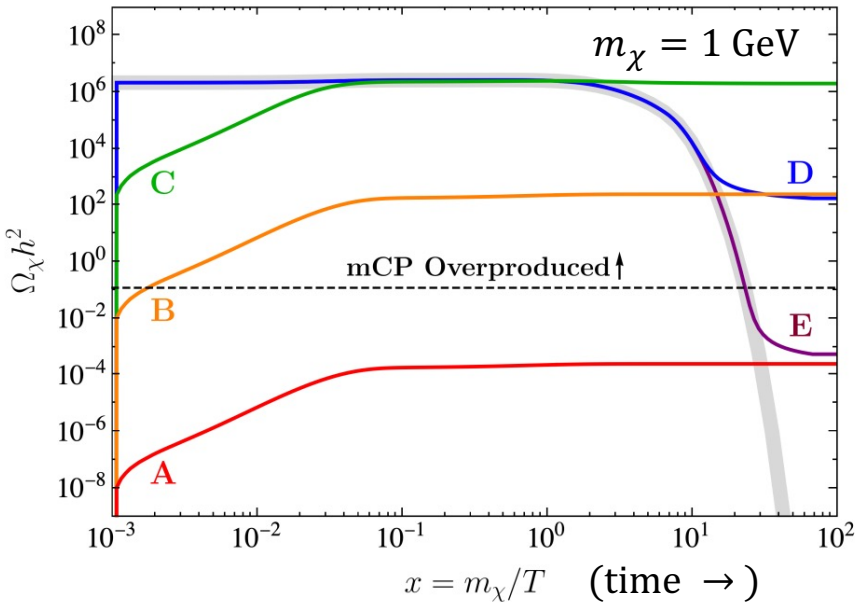
$$\rho_{\rm c} = \frac{3H^2}{8\pi G}$$

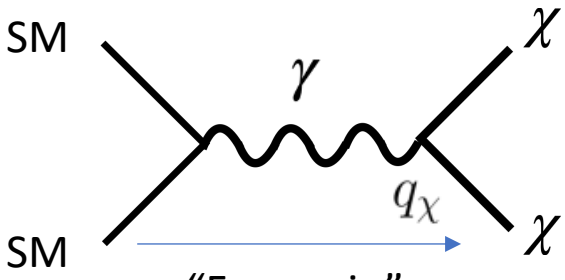
“Pure” CmB Cosmology: Freeze-in and Freeze-out

T_{rh} = 1 TeV (or above)

$\epsilon = Q_x/e$







“Freeze-in”

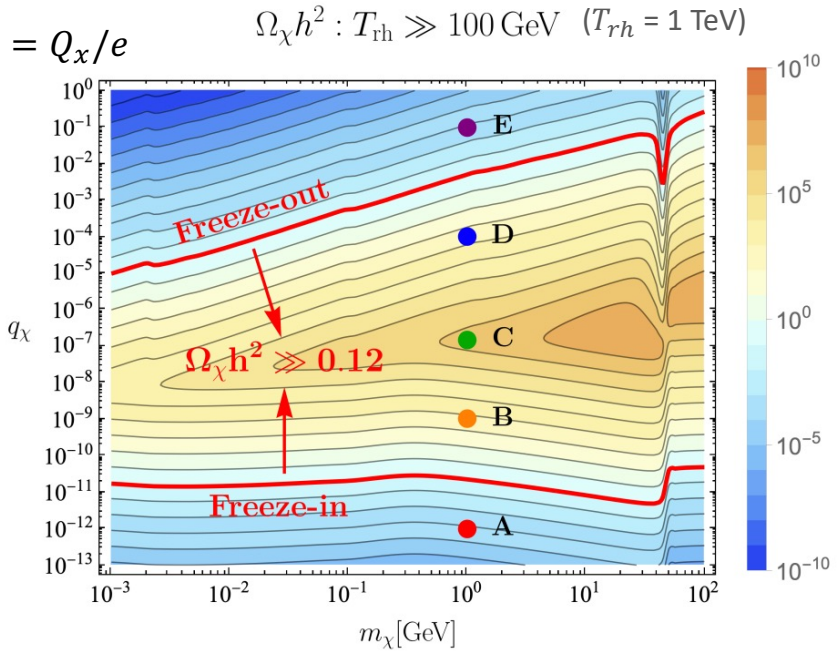
“Freeze-out” when it stops

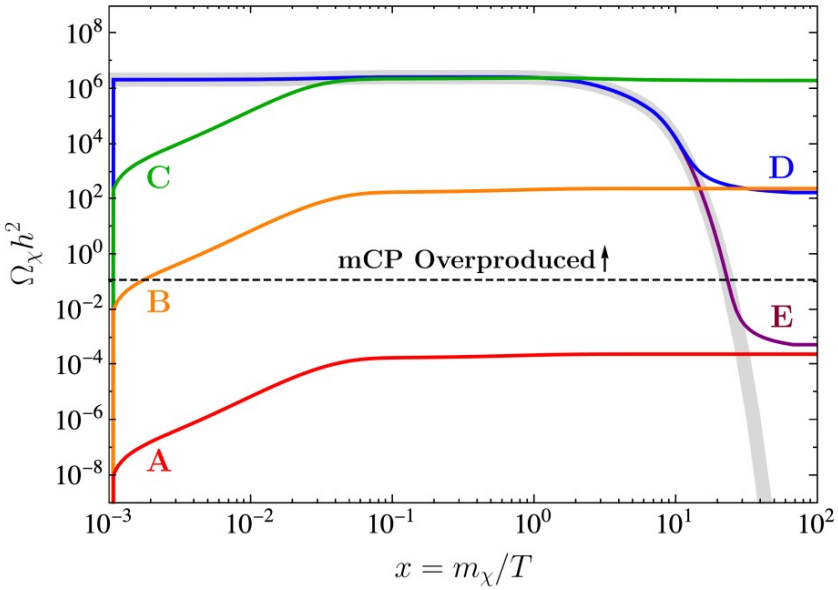
$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\rm eq}^2}\right),$$

$$\mathcal{C}_n(T) = 2n_Z\langle\Gamma\rangle_{Z\to\chi\bar{\chi}} + 2n_f n_{\bar{f}}\langle\sigma v\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

“Pure” CmB Cosmology: Freeze-in and Freeze-out

$\epsilon = Q_x/e$





Freeze-in: $$Y_\chi^{\rm FI} \sim q_\chi^2 \alpha_{\rm em}^2 \frac{m_{\rm pl}}{T}, \quad T \gtrsim m_\chi.$$

Freeze-out: $$Y_\chi^{\rm FO} \sim \frac{1}{q_\chi^2 \alpha_{\rm em}^2} \frac{m_\chi}{m_{\rm pl}},$$

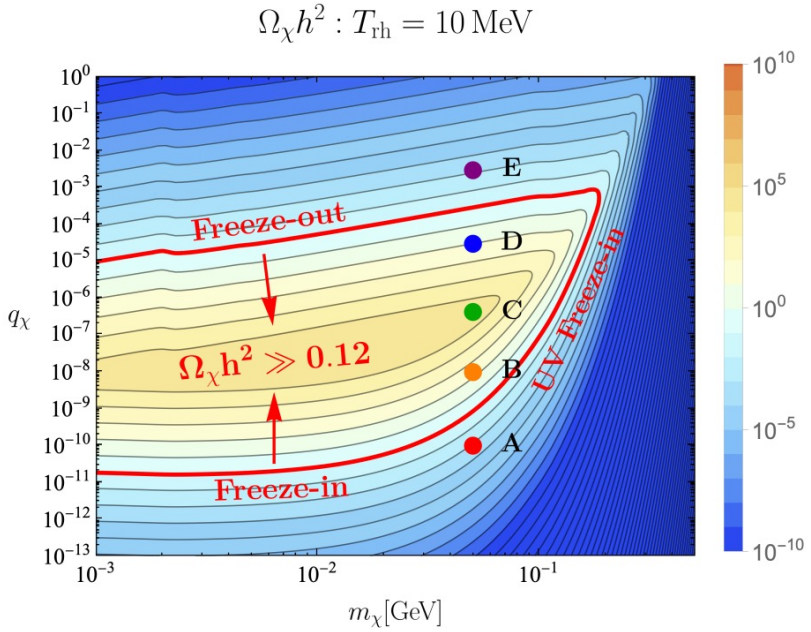
$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\rm eq}^2}\right),$$

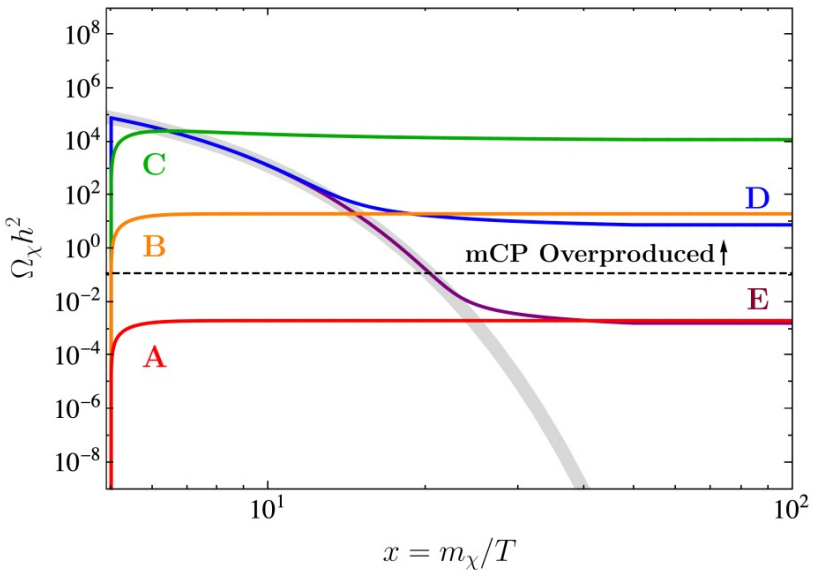
$$\mathcal{C}_n(T) = 2n_Z\langle\Gamma\rangle_{Z\to\chi\bar{\chi}} + 2n_f n_{\bar{f}}\langle\sigma v\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

See, e.g., Vogel, Redondo, JCAP (2014), Dvorkin+, PRD (2019)

“Pure” CmB Cosmology: Low-Reheat Temperature

T_{rh} = 10 MeV



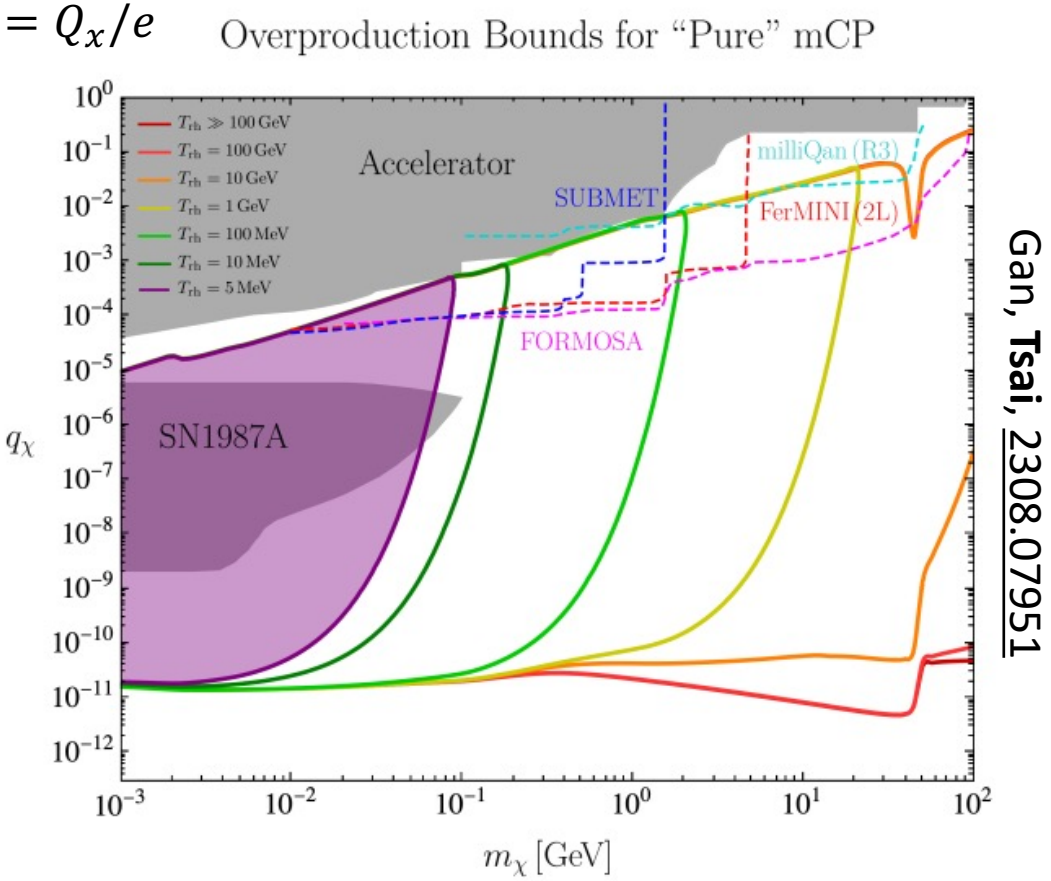


For the freeze-in at low T_{rh}, mCP-SM interaction is suppressed exponentially: the coupling has to increase exponentially to compensate it

The freeze-in curve holds the approximate relation: $q_\chi \propto \exp\left(\frac{m_\chi}{T_{\rm rh}}\right)$

“Pure” CmB from Irreducible Production

$\epsilon = Q_x/e$



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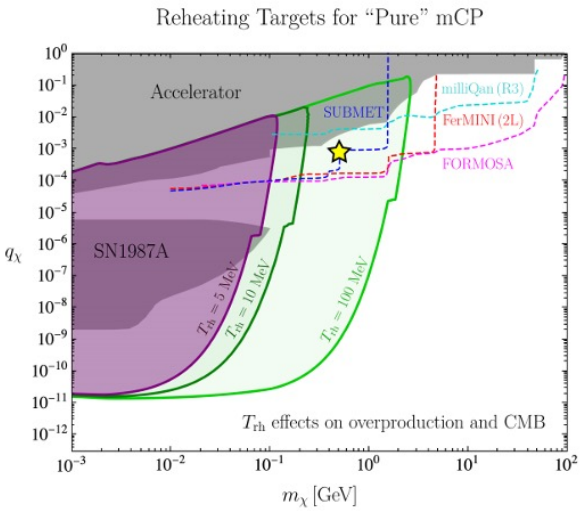
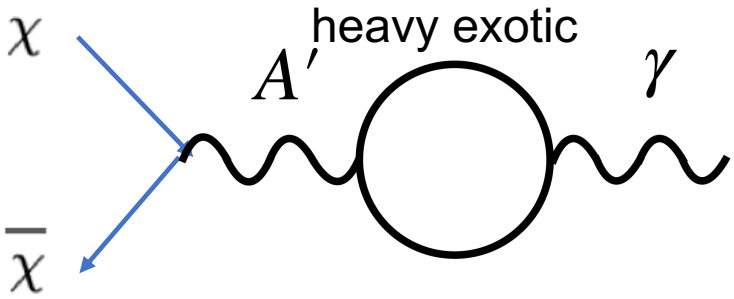


- Minimal reheating temperature larger than T_{BBN} (e.g., Hasegawa+, JCAP19; Hannestad, PRD04)
- **Our purple bound is covering the SN1987A constraint** (gray region from Chang+, JHEP18)

Kinetic-Mixing Cosmic Millicharge Background (CmB)

Kinetic-mixing mCP



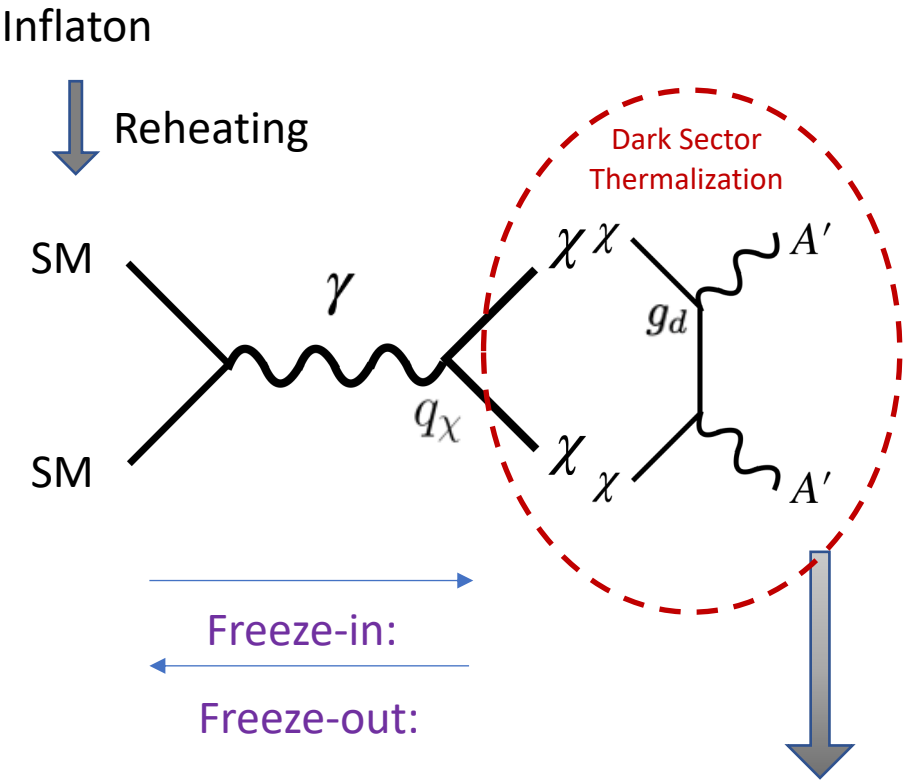
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\rm MCP})\chi$$

Choose a proper basis:
massless dark photon A' decouple from SM

$$q_\chi = \frac{\epsilon g_d}{e}$$

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' eA\!\!\!/ + M_{\rm MCP})\chi$$

Kinetic-mixing mCP



massless dark photon A' will affect N_{eff}
See Vogel, Redondo, JCAP (2014),
Adshead, Ralegankar, Shelton JCAP (2022)

Kinetic-Mixing CmB Cosmology:

N_{eff} Effects from Dark Photon

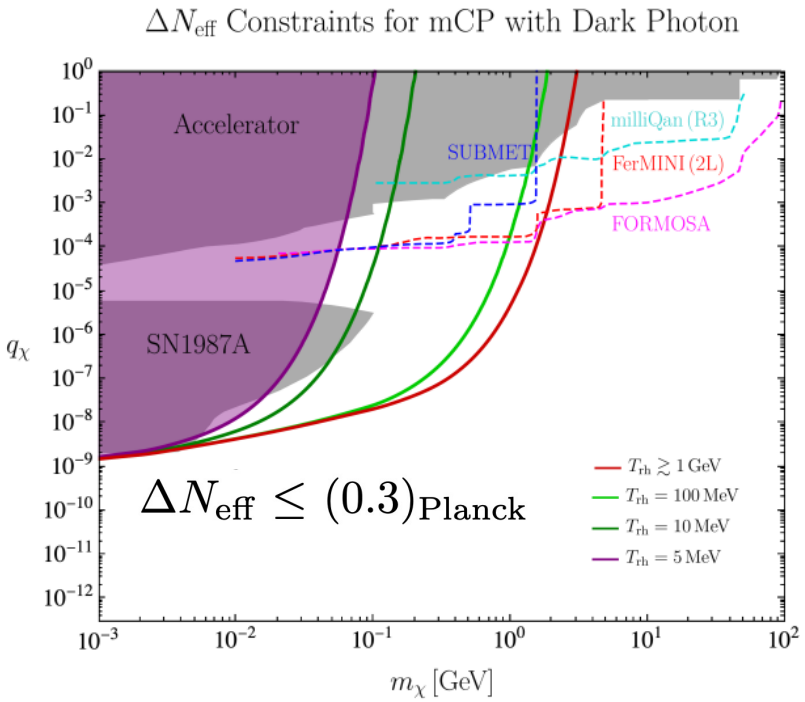
- Freeze-in from the heat bath
- χ thermalizing with dark photon: Require effective transfer of χ entropy to dark radiation A' here

$$\frac{n_\chi^{\rm FI}\langle\sigma v\rangle_{\rm dth}}{H} \sim q_\chi^2 \alpha_{\rm em}^2 \alpha_d^2 \left(\frac{m_{\rm pl}}{T}\right)^2 \gg 1.$$

$$\alpha_d \gg 10^{-4}$$

- A quick ΔN_{eff} estimation:

$$\Delta N_{\rm eff} \sim q_\chi^2 \alpha_{\rm em}^2 \frac{m_{\rm pl}}{m_\chi}$$



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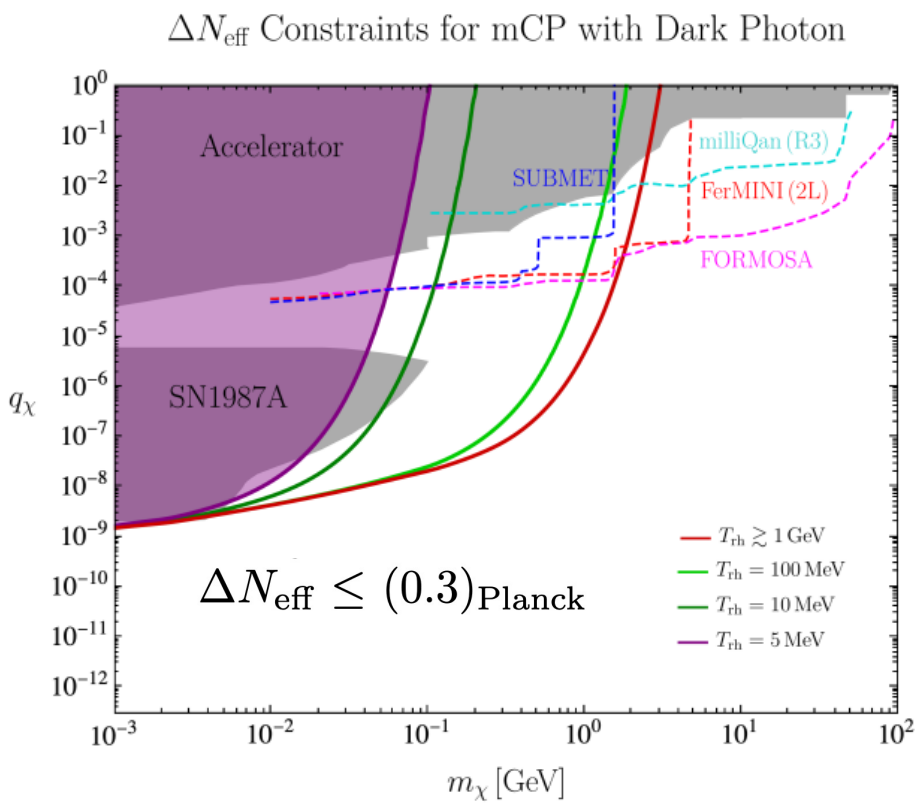
- **Our purple bound is again covering the SN1987A constraint**

Kinetic-Mixing CmB Cosmology



$$q_\chi \sim 10^{-7} \left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)^{1/2} \left(\frac{\Delta N_{\rm eff}}{0.3}\right)^{1/2} . \; m_\chi \leq \mathrm{T_{rh}}$$

$$q_\chi \propto \exp\left(\frac{m_\chi}{T_{\rm rh}}\right) . \; m_\chi > \mathrm{T_{rh}}$$

Considering higher reheating temperatures for region to the right of the red curve:

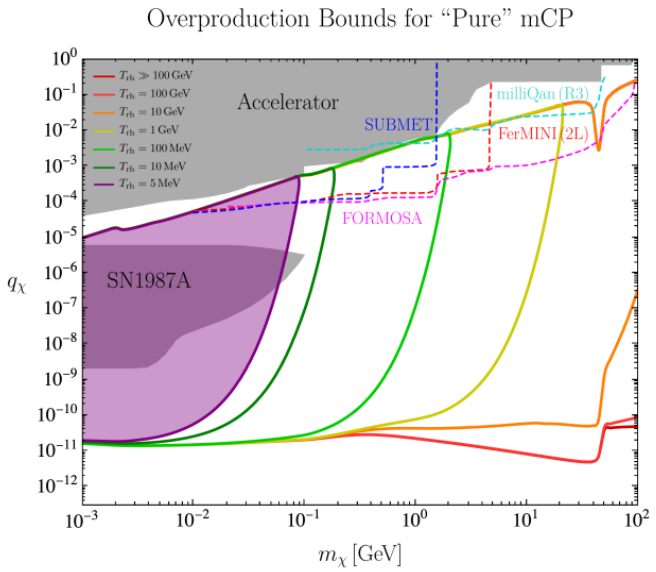
$$\Delta N_{\rm eff} \lesssim g_{A'} \, \frac{4}{7} \left(\frac{g_{*,S}(T \ll T_{\rm QCD})}{g_{*,S}(T \gg T_{\rm QCD})}\right)^{4/3} \simeq 0.1,$$

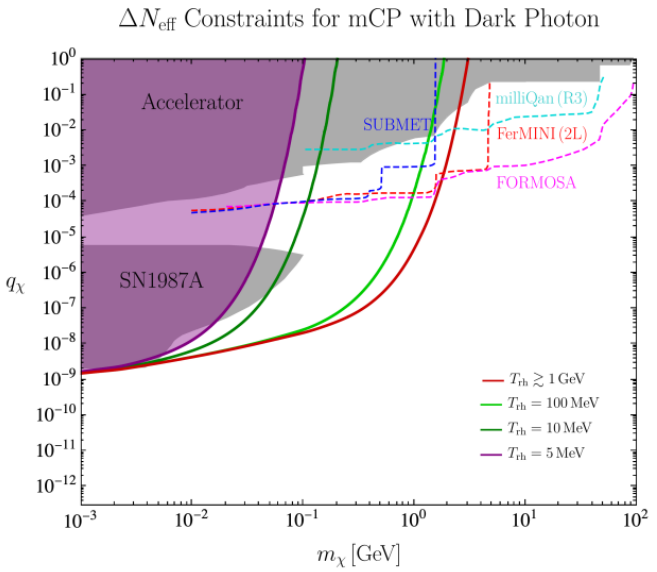
See Gan, **Tsai**, 2308.07951 for detailed discussions

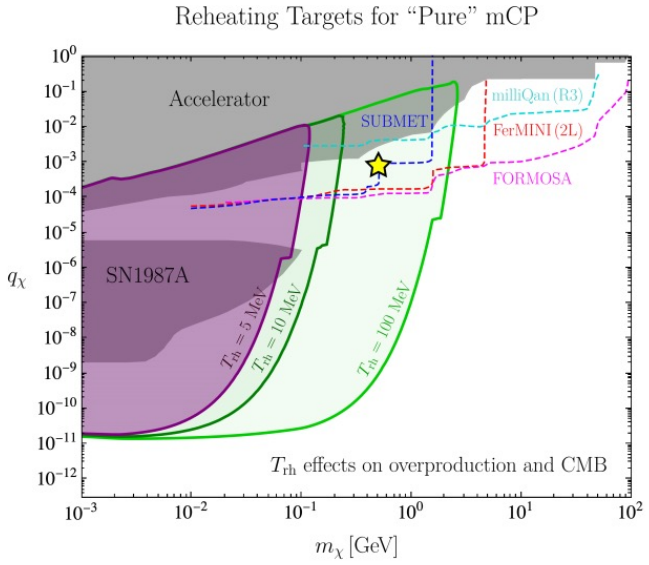
Current: $\Delta N_{\rm eff} \leq (0.3)_{\rm Planck}$

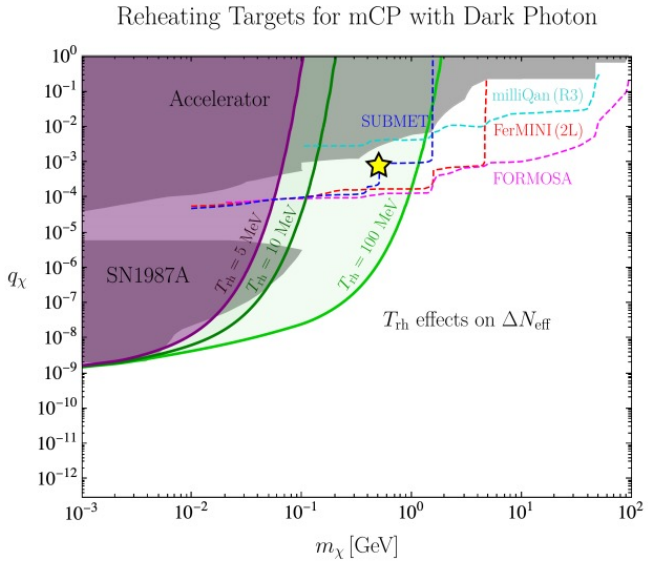
Future: $\Delta N_{\rm eff} \leq (0.06)_{\rm CMB\text{-}S4}$

Testing Reheat Temperatures in Both Cases



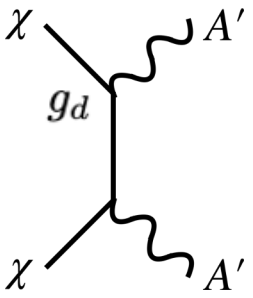




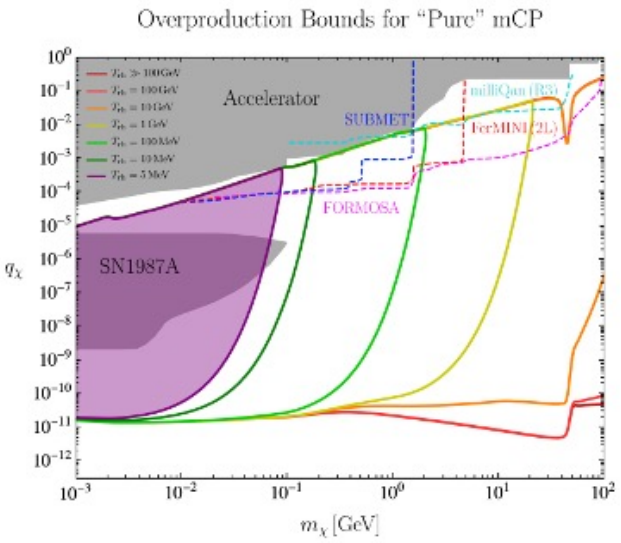


Another Key Objective:

Differentiate Two Types of MCPs



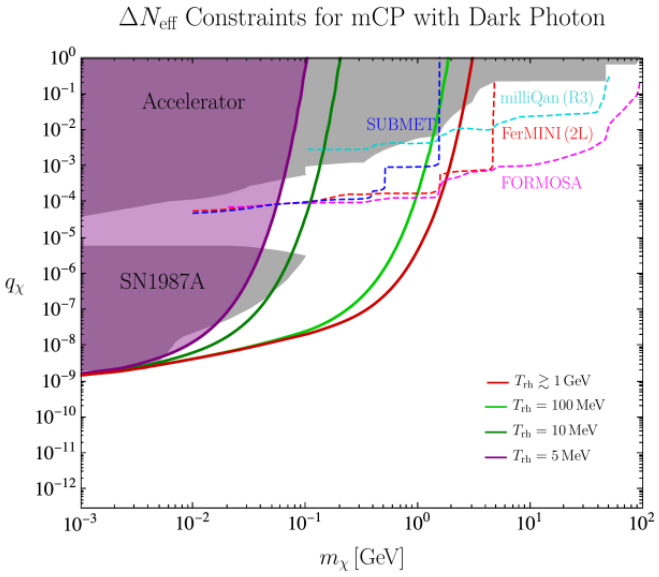
$g_d = 0$



modifying g_d

Interpolate between the two

Sizable g_d



Theoretically, there is a limit on how small g_d can be, for a given q_χ

"Distinguishability" Conditions

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- Turning down thermalization between $\chi - A'$: $g_d \lesssim (16\pi^2 m_\chi / \mathcal{F} m_{\rm pl})^{1/4}$

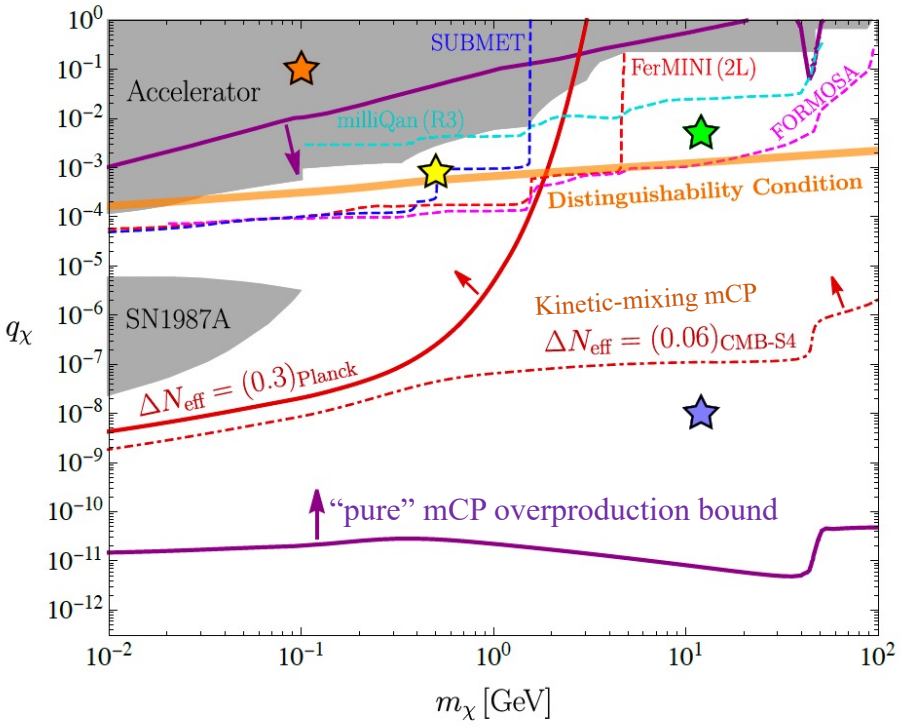
- Requirement for kinetic mixing: $\epsilon < 1 \quad \Rightarrow \quad g_d > e q_\chi, \quad q_\chi = \frac{\epsilon g_d}{e}$
  Burgess *et al*, JCAP (2008)

- Considering these two inequalities for gd, we can roughly determine that:

$$q_\chi \gtrsim \frac{1}{\alpha_{\rm em}^{1/2}} \left(\frac{m_\chi}{\mathcal{F} m_{\rm pl}} \right)^{1/4}$$

One CANNOT de-theramlize $\chi - A'$ interaction rate to mimic "pure" mCP!

Regions of Interests



- **Orange Star:** favoring "pure" mCP
- **Yellow Star:**

  testing reheat temperatures
- **Green Star:**

  1) testing reheat temperatures with CMB-S4

  2) currently favoring kinetic-mixing mCP
- **Purple Star:** favoring kinetic-mixing mCP

  (can be reached by direct-detection exps.)

Frederick Reines

Nobel Prize Laureate; Professor at UC Irvine

Utilized a **nuclear reactor to study free neutrinos**

We have an opportunity to explore the millicharge dark sector and unveil deep mysteries of the Universe

Thank you!